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Rheinhardt Scholtz

Oklahoma State University, r.scholtz@unl.edu

Samuel D. Fuhlendorf

Oklahoma State University, sam.fuhlendorf@okstate.edu

Sherry A. Leis

National Park Service

Joshua J. Picotte

EROS Center

Dirac L. Twidwell Jr

University of Nebraska-Lincoln, dirac.twidwell@unl.edu

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Quantifying variance across spatial scales as part of fire regime classifications

RHEINHARDT SCHOLTZ ^{1,†} SAMUEL D. FUHLENDORF,¹ SHERRY A. LEIS,²
JOSHUA J. PICOTTE,³ AND DIRAC TWIDWELL⁴

¹Department of Natural Resource Ecology and Management, Oklahoma State University, 008D Agricultural Hall, Stillwater, Oklahoma 74078 USA

²National Park Service, Heartland Inventory and Monitoring Network, 6424 West Farm Road 182, Republic, Missouri 65738 USA

³Earth Resources Observation and Science (EROS) Center, ASRC Federal InuTeq, Contractor to the U.S. Geological Survey (USGS), 47914 252nd Street, Sioux Falls, South Dakota 57198 USA

⁴Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, Nebraska 68583 USA

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Abstract. The emergence of large-scale fire classifications and products informed by remote sensing data has enabled opportunities to include variability or heterogeneity as part of modern fire regime classifications. Currently, basic fire metrics such as mean fire return intervals are calculated without considering spatial variance in a management context. Fire return intervals are also only applicable at a particular grain size (defined as the spatial unit of interest) even though they are typically applied homogeneously. In this study, we utilized a 29-yr fire occurrence database to show how spatial variance changes with respect to grain as postulated by Wiens (1989) when reporting fire patterns within the Great Plains, USA. We utilized data from the Monitoring Trends in Burn Severity database of fire occurrence for the years 1984–2012. We analyzed median numbers of fire along with their variance at four spatial grains ranging from small units (e.g., plots at 3 × 3 km resolution) to large units (e.g., landscapes at 1500 × 2700 km resolution). Median number of fire occurrences was consistently low, irrespective of grain. Despite the consistency in low median numbers of fires across grain, variance in the numbers of fires between units decreased. Variance within units, however, did not change as grain increased indicating fire-pattern-scale inconsistencies. Fire pattern interpretations depended entirely on the scale at which it is calculated. Given that the Great Plains region has a large disparity in fire patterns (i.e., some regions burn often, while others may never burn), fire regime classifications will benefit from including scale-specific variance estimates as a foundation for understanding changes in fire regimes and corresponding social–ecological and policy responses.

Key words: ecoregions; fire occurrence; mean fire return intervals; prescribed fire; wildfire.

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† E-mail: r.scholtz@okstate.edu

INTRODUCTION

Ecological processes and patterns including wildfire generally vary when observed across different spatial and temporal scales (Wiens 1989, Levin 1992, Leibold et al. 2004). For example, frequent fire is important to structure and function of dynamic ecosystems such as savannas and

grasslands (Bond and Van Wilgen 1996). Furthermore, responses by these ecosystems are dynamic within a spatiotemporal landscape context (Fuhlendorf and Smeins 1996, Fuhlendorf et al. 2002). As a consequence, vegetation dynamics depend on several factors such as geology, topography, fire activity, and rainfall interacting at various scales (Smit et al. 2013, Vaughn et al. 2015, Scholtz et al. 2018).

Despite the importance of fire patterns at local, regional, and global scales (Bond and Keeley 2005, Bond et al. 2005), variability in grassland fire pattern with respect to spatial scale is seldom studied. In forest fire regimes, however, spatiotemporal fire patterns are often based on studies of fire scars, which are formed in the growth rings of trees, to explore past low-severity fire regimes (Falk et al. 2007, 2011). Investigation of mean and variance of fire classifications across spatial and temporal scales is rarely the focus of modern fire regime classification. However, a few studies have acknowledged the importance of understanding fire regime classification with respect to fuels management, fire risk, and ecological impacts, particularly with respect to a changing climate (Morgan et al. 2001). Nevertheless, nearly all global and continental classifications use the mean fire return interval (MFRI) as the basis for classifying fire regimes. Mean fire return intervals:

$$\text{MFRI} = \frac{\text{years of observation}}{\text{number of fires}} \quad (1)$$

Mean fire return interval calculated for a specific period of time is a useful and easy metric to supply to fire practitioners. Mean fire return interval and similar calculations generally provide regional guidelines for fire treatments (e.g., Rollins 2009). However, they have yet to include corresponding information about the relationships between the mean and variance as the spatiotemporal scale of analysis changes. With the emergence of large-scale fire classifications such as LANDFIRE (Rollins 2009; <https://www.landfire.gov>) and products informed by remote sensing data (Monitoring Trends in Burn Severity [MTBS]; Eidenshink et al. 2007; <https://www.mtbs.gov>), there are opportunities to include variability/heterogeneity estimates as part of modern fire regime classifications.

Although multiple studies have highlighted the importance of spatial scale (Wiens 1989) when quantifying ecological processes (e.g., Fuhlendorf and Smeins 1999, Fuhlendorf et al. 2002, Convertino et al. 2011, Smit et al. 2013), it remains a challenge to apply the principles of spatial scale to land management and policy development. In this study, we are particularly interested in how fire patterns may differ depending on which spatial scale is considered. These and similar scaling

challenges have recently received a substantial amount of attention within various disciplines (e.g., Cale and Hobbs 1994, Cash et al. 2006, Moss and Newig 2010).

Wiens (1989) presented a hypothesis that attempts to understand how variance changes with spatial scale. In general, as sample grain (i.e., size of individual units of the study) becomes larger, spatial variance as a whole decreases either homogeneously or heterogeneously (Fig. 1a). Furthermore, with increasing grain, less of the variance was due to differences between samples and more of the overall variation was included within samples. The opposite relationship was hypothesized when comparing variance within units (Fig. 1b).

Fire is an integral process in maintaining landscape heterogeneity and, subsequently, biological diversity especially in grasslands and savannas (Fuhlendorf and Engle 2001, Fuhlendorf et al. 2006, Hovick et al. 2014, Ratajczak et al. 2014). By only focusing on mean intervals, calculations of historical grassland fire regimes have failed to capture the metrics of variance. Fire occurrence over the Great Plains, USA region, in particular,

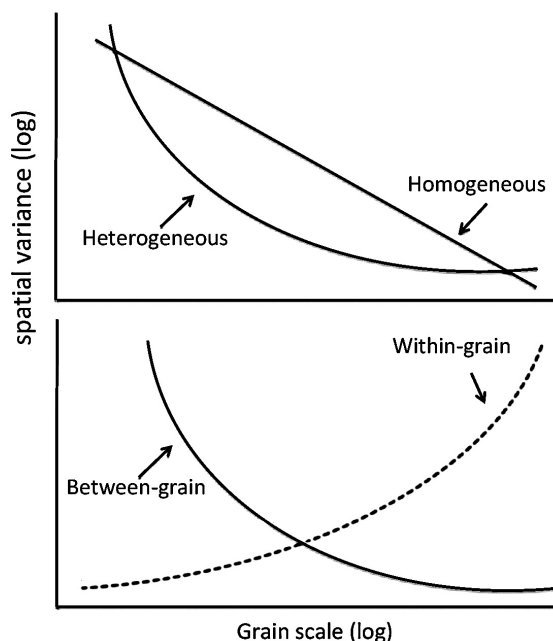


Fig. 1. Representation of the effect of grain size on spatial variance (Figure 2 Wiens (1989) reproduced with permission).

has fluctuated drastically in recent decades due to a number of decoupled forces acting upon it, for example, fire suppression and fire increase in areas where prescribed burn associations (PBAs; landowners assisting one another during burn events) are active as well as climate variability (Tilman et al. 2000, Krueger et al. 2015, Twidwell et al. 2015, Petrie et al. 2016, Weir et al. 2016, Donovan et al. 2017). Landowner assistance through PBAs has been established as a model to support application of fire on private lands in rangelands. Prescribed burn associations provide training, equipment, and labor to apply fire safely and reduce the associated risk (Toledo et al. 2014).

Furthermore, recent threats in the Great Plains region to natural processes such as fire and other ecosystem services by conversion to agriculture and energy development continue on large tracts of grassland (Allred et al. 2015). Since methods of understanding fire occurrence patterns at multiple scales are not defined (Twidwell et al. 2013), this study provides a unique opportunity to quantify spatial variance in fire occurrence over the 29-yr time period and discover how spatial variance can be incorporated into future fire policies and classifications (Morgan et al. 2001). Our aim was to determine how the mean return interval and spatial variance in fire occurrence change as a function of spatial grain at the sub-continental scale of the Great Plains, USA. We tested Wiens' (1989) hypothesis using this fire dataset and discuss how understanding variance will be valuable for landowners, policy-makers, land managers, and scientists alike. The major departures in scale-specific calculations of mean and variance are critical to understanding the continued trend of woodland expansion into regions like the grasslands of the Great Plains (Twidwell et al. 2013, Ratajczak et al. 2016).

METHODS

Study area

The Great Plains (excluding the easternmost states of the United States typically included in the region) was defined as the extent for this study and was one of 15 Level 1 ecoregions (Omernik 1987) within the continental United States (Fig. 2). While the Great Plains ecoregion extends into Canada, only data from continental

United States were considered in this study. Vegetation in the region is comprised mainly of grasslands with interspersed stands of woody vegetation. Shortgrass prairie is more common in the west and tallgrass prairie in the eastern Great Plains (Omernik 1995). The southeastern part of the region receives the most rainfall (mean annual precipitation [MAP] ~1600 mm) with drier areas to the west and north (MAP ~200 mm; Lauenroth et al. 1999).

Data source

Locations of reported fires were sourced from the MTBS database (Eidenshink et al. 2007) for the study area for the years 1984–2012. Monitoring Trends in Burn Severity used Landsat imagery to detect and georeference fires. Only the MTBS georeferenced fires (e.g., wildfires, prescribed fires, fire of an unknown ignition source, and wildfire use) were used in this study. Only large fires ≥ 404 ha (1000 acres) were captured by the MTBS project (further details on data collection can be obtained at <https://mtbs.gov/map-ping-methods>) and used in this study.

Data preparation and analyses

Fire occurrence data were aggregated to four spatial grains (units) as described in Figs. 3, 4 within the extent. The extent was defined as the entire study area, that is, the Great Plains as shown in Fig. 2 (Level 1, Omernik 1987). We set out to increase the grain size by a factor of 10, where possible, to mimic incremental increases in grain on the logarithmic scale. The smallest grain was 3×3 km units. Because we had GPS (global positioning system) locations of fire ignition points, a grain of 3×3 km was sufficient to distinguish between units that experienced many fire occurrences and units that experienced few fire occurrences in order to calculate variance at this grain. For the next grain, fire records were aggregated by a factor of 10– 30×30 km units by taking the average of the number of fire occurrences. For the next grain, fire records were aggregated by a factor of 100 to the 300×300 km units by average. Finally, small units were aggregated by a factor of 890 to obtain $\sim 1500 \times 2700$ km units by average before aggregating data to the extent itself (where variance cannot be calculated because the number of fire occurrences over the entire region is represented

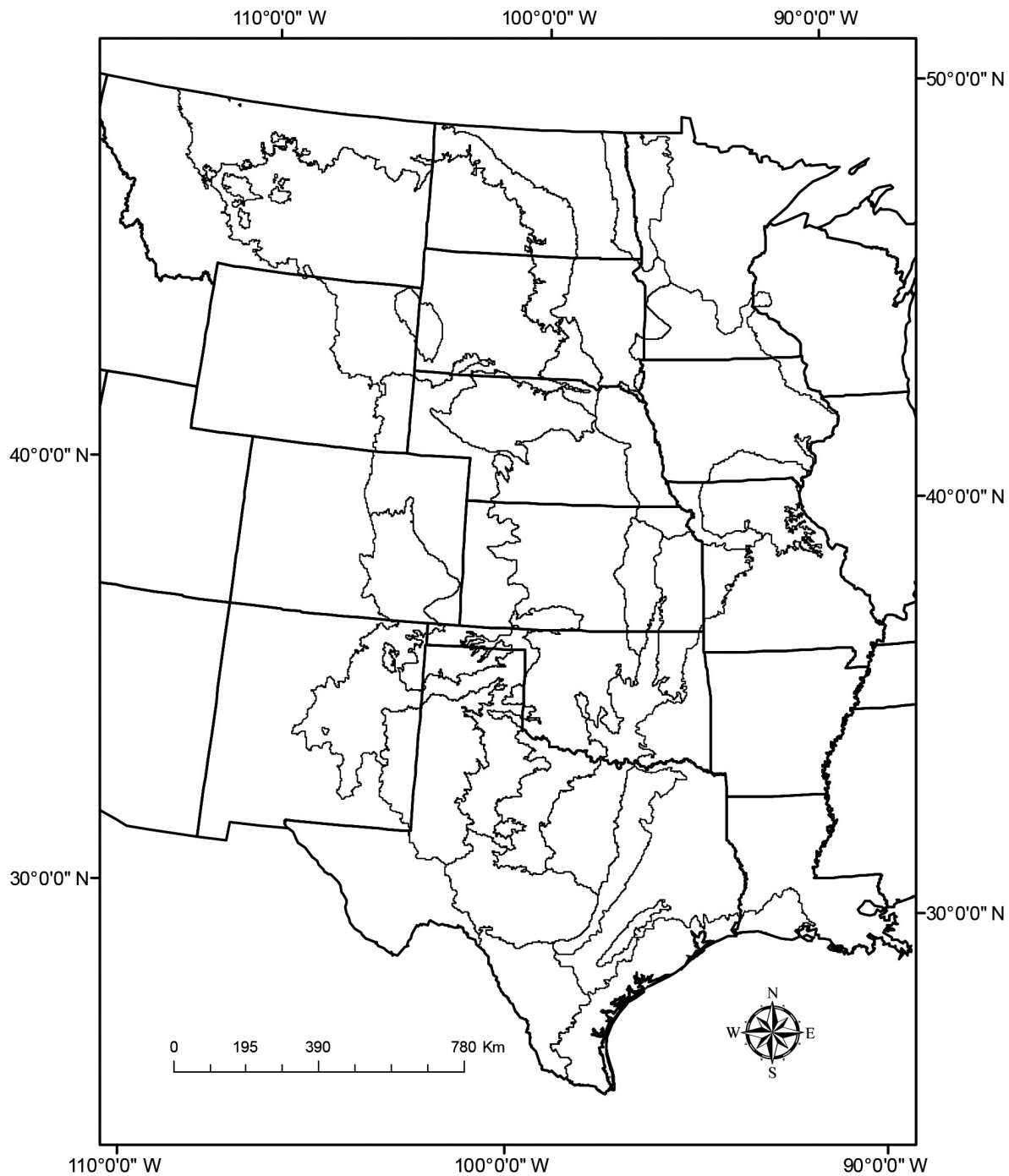


Fig. 2. Map showing the states within the central United States (thick lines) and the ecoregions (Level 3, Omer-nik 1995) that make up the Great Plains (thin lines), which was used as the extent for this study.

by a single number). While aggregating to each grain often results in a square or rectangle, particularly as grain approaches the extent, our resulting aggregation was masked cut to the

shape of the extent prior to variance calculations. (1) Between-unit variance (Fig. 3) and (2) within-unit (Fig. 4) variance were calculated at each grain while maintaining the extent (Fig. 2). The

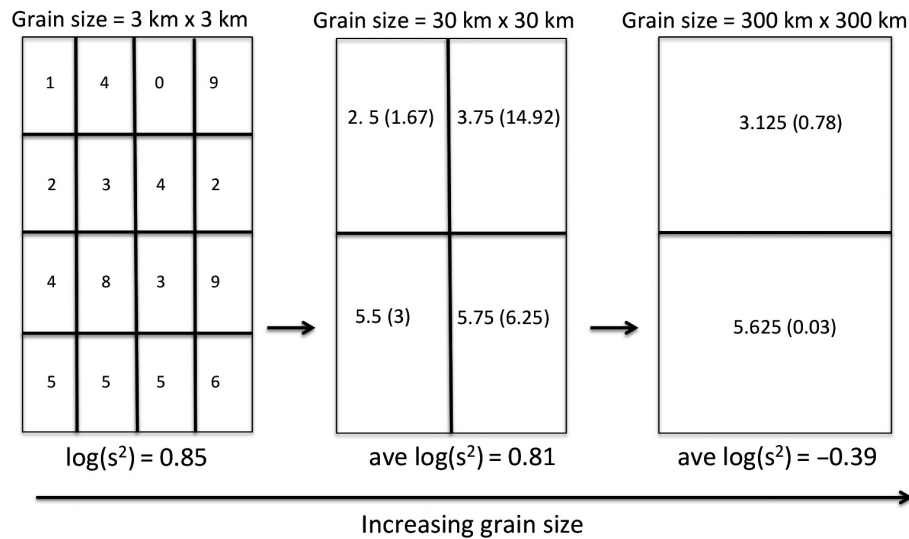


Fig. 3. Diagrammatic representation showing an example of how the numbers of fires were aggregated by average and variance (s^2) between units was calculated at each grain. As grain increases, variance between units is calculated and averaged. The extent is the outer edge, and the grain size is the inner box.

(1) between-unit spatial variance (s^2) was calculated as shown in Eq. 2 using the numbers of unique fire records (i.e., GPS locations) at each grain (Fig. 3). Sample sizes at each grain are provided in Table 1.

The (2) within-group spatial variance (s^2) was calculated as shown in Eq. 2 as follows. The variance within units of the medium grain (30 × 30 km) represented the smallest grain. Here, we aggregated the smallest grain (3 × 3 km units) by

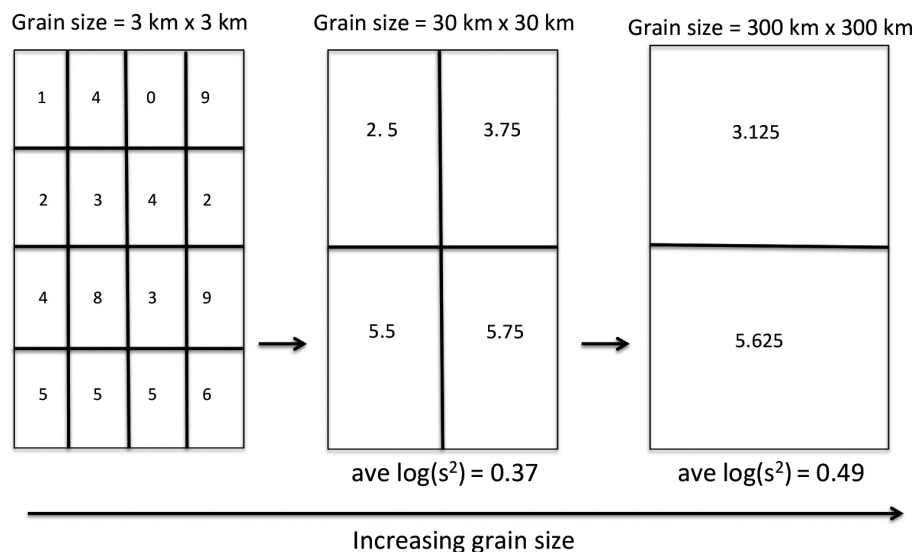


Fig. 4. Diagrammatic representation showing an example of how the numbers of fires were aggregated by average and variance (s^2) within units was calculated at each grain. Here, we do not calculate variance at each individual unit; rather, the average variance is calculated for the aggregated values as grain size increases. The extent is the outer edge, and the grain size is the inner box.

Table 1. Median (50th percentile), 95th percentile, and minimum and maximum numbers of fires as well as the mean fire return interval (MFRI) in years at each grain in the Great Plains region.

Units (grain; km)	<i>n</i>	Median	95th	Min–Maxm	% area burned	MFRI
3 × 3	219,384	0	0	0–17	1.75	0.008
30 × 30	2373	0.01	0.09	0–1.71	52.76	0.023
300 × 300	37	0.01	0.08	0–0.12	94.60	0.839
1500 × 2700	2	0.01	0.02	0–0.02	50	29

Note: % Area burned is the number of pixels with a fire recorded/total number of pixels (*n*) per unit (×100).

a factor of 10, calculated the variance within the units representing this grain. The same steps were taken to aggregate up to the next grain size (large units were aggregated by a factor of 100 and extra-large by a factor of 890), and the variance within the units was calculated at each grain size. Similarly, there is no variance in fire counts within the smallest grain (i.e., 3 × 3 km units), the scale at which data were collected (Fig. 4).

Variance (s^2) at each grain was calculated as follows:

$$s^2 = \frac{\sum (x_i - \bar{x})^2}{n - 1} \quad (2)$$

To test Wiens (1989) hypothesis, the logarithmic transformation of variance was taken at each grain. Furthermore, we counted the number of units contributing to the variance (i.e., experienced >0 fires) at each grain and calculated the percentage burned area as well as the minimum and maximum numbers of fires at each grain. The MFRI at each grain was calculated using Eq. 1.

RESULTS

The median number of fire occurrences did not differ by grain, while the maximum numbers of fires decreased with increasing unit size from the smallest to the largest spatial grain (Table 1). The area (%) that experienced fire activity also varied with spatial grain where the lowest fire activity (%) was recorded in the 3 × 3 km unit and the highest in the 300 × 300 km unit. The MFRI (years) increased with scale by orders of magnitude (Table 1).

Log variance between units decreased as grain size increased from the small to large, while no changes in log variance within units were observed as grain size increased from small to medium (Fig. 5).

The observed pattern in the total number of fire occurrences changed as the scale increased from plot to ecoregion (Fig. 6). In summary, as a result of most of the area not containing a fire, the median number of fire occurrences was consistently low or equal to zero across unit sizes while the maximum decreased as grain increased. Mean fire return interval increased as grain increased and the log variance between units decreased as grain increased, while the within-unit relationship was relatively similar across grain sizes. Overall, fire metrics (e.g., return interval, number of fire occurrences, and % area burned) were highly dependent on the grain of interest highlighting the importance of scale in fire pattern interpretations.

DISCUSSION

Our study aimed to understand patterns in variance of the number of fire occurrences as grain size changes by testing Wiens' (1989) hypothesis. We demonstrate that fire metrics, such as MFRI while useful, are incomplete since they do not consider scale-dependent variance as predicted by Wiens (1989). Our analysis indicated that interpretation of fire patterns is strongly influenced by spatial grain. Fire is a critical process for maintaining grasslands, and interpretation of fire occurrence data has implications for future fire management. Even though fire frequency often declines as non-fire-prone landscapes (e.g., agricultural land) expand, a scaled approach to understanding fire occurrence is valuable (Ratajczak et al. 2014, Andela et al. 2017, Archer et al. 2017). We found that fire return metrics are only valid at the scale at which they were quantified and should not be applied across multiple scales.

When we compared variance between units, variance decreased as grain size increased as

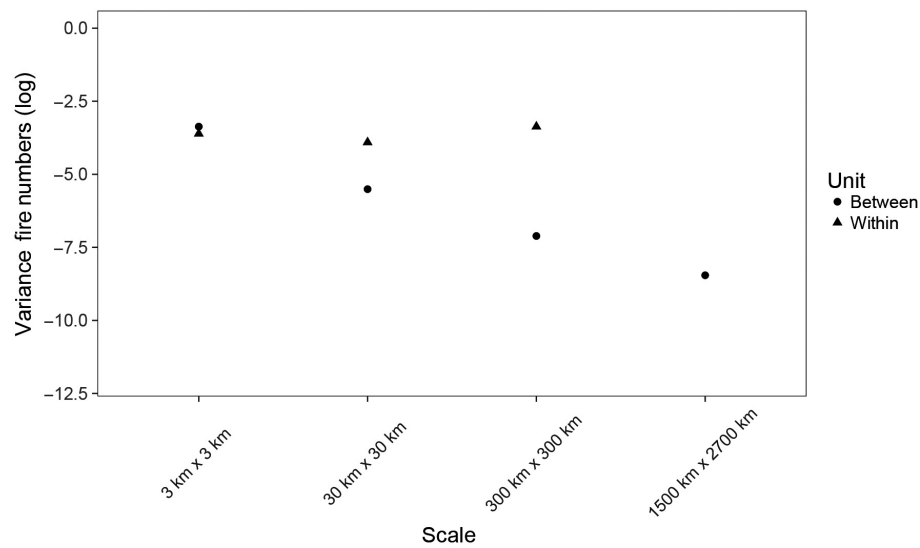


Fig. 5. The log (variance) in the numbers of fires at each grain (y -axis) between and within units as grain increases (x -axis). Circles show the log (variance) between units, while triangles show the log(variance) within units.

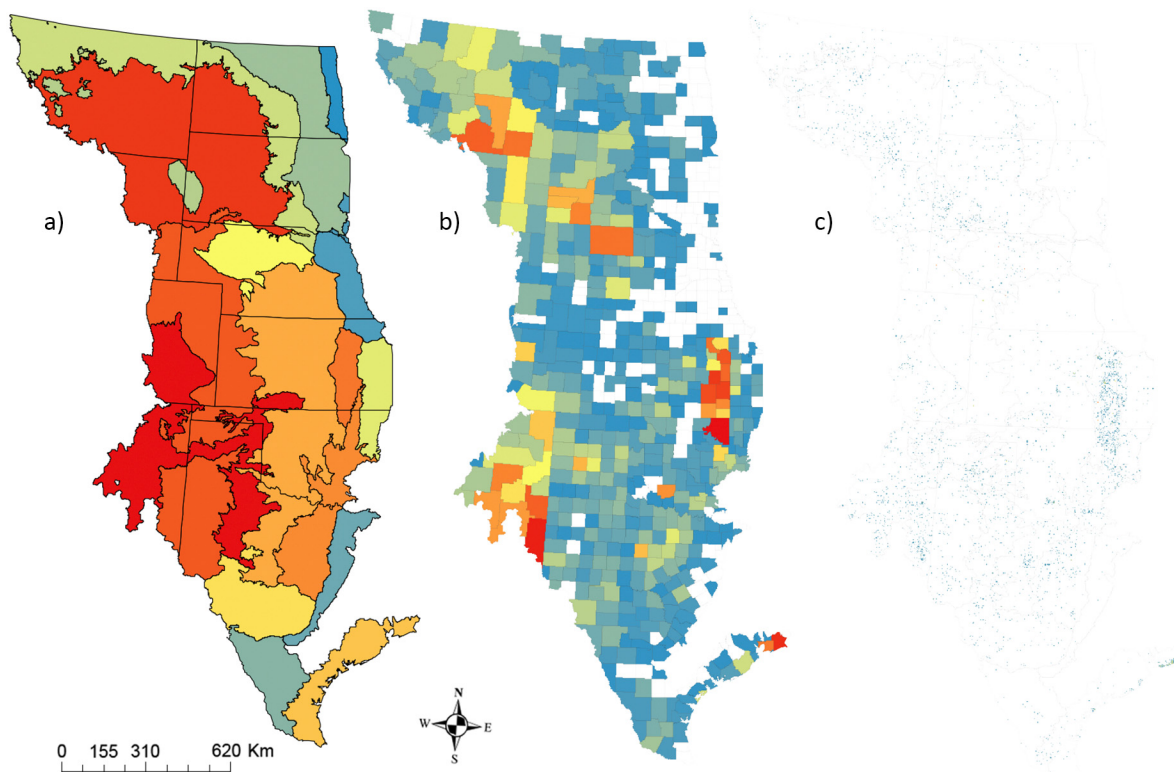


Fig. 6. Interpretation of the number of fire occurrences between 1984 and 2012 changes as the observational scale changes leading to differing interpretation of fire activity and pattern as scale changes. Panels represent the (a) ecoregion, (b) municipal county, and (c) plot (3×3 km) scales. For panels (b) and (c), red refers to high fire occurrences, blue refers to low fire occurrences, and clear refers to zero fire occurrences.

predicted by Wiens (1989). We did not, however, observe Wiens' (1989) predictions when considering log variance within units (Fig. 5). Thus, variance did not increase as predicted by Wiens (1989); rather, variance remained relatively stable as spatial grain increased. This could be related to disconnected patterns of fire within the region irrespective of scale. For example, the study area contains several ecoregions, that is, areas with a similar environmental template (Level 3; Omernik 1995) and some municipal counties within these ecoregions that contain high numbers of fire (e.g., the Flint Hills, Mohler and Goodin 2012). This inconsistency was very clear in Table 1 which shows that, at intermediate scales, >90% of the area experienced one fire, suggesting that most of the area burned. But, drastic differences in fire occurrences (1984–2012) were observed as the spatial grain changed from plot scale (3×3 km) to municipal county scales, and finally to the ecoregion scale. This analysis clearly demonstrates that interpretation of fire patterns changes with observational scale (Fig. 6, Table 1).

Most of the study area experienced low numbers of fire. It is clear that certain areas burn frequently while others do not, thereby resulting in variable patterns of fire occurrence at multiple scales. Seasonal differences in fire probability (Appendix S1: Fig. S1) showed that most southern central states (e.g., OK, TX, KS, MO, and NE) use prescribed fires primarily during the dormant season (November–April; Knapp et al. 2009, Mohler and Goodin 2012), while northern states (e.g., SD and ND) use fire less frequently (Symstad and Leis 2017). However, we acknowledge that there are large tracts of agricultural land in the study, which usually do not burn. The ecological importance of these remaining grasslands and the role of fire in sustaining them are therefore critical (Bond and Keeley 2005, Anderson 2006, Scholtz et al. 2018).

Our study used mean number of fire occurrences and variances as grain changes to highlight that Wiens (1989) hypothesis is only partly supported. Variable usage of fire (e.g., some grasslands burn more often than others) in the region results from many sources including but not limited to the following: cultural acceptance, fire suppression policies, grassland loss to agriculture, woodland expansion, and energy

development (Bradford et al. 2005, Toledo et al. 2014, Allred et al. 2015, Scholtz et al. 2017, Symstad and Leis 2017). Despite the range of fire use (e.g., wildfires and prescribed fires) in grasslands within the region, most studies provide inferences based on average fire activity such as MFRI which homogenizes a very heterogeneous fire system (Fuhlendorf et al. 2006). In forest systems, however, calculation of fire history from tree fire scars reveals low-severity fire regimes in the past (Halofsky et al. 2011); however, certain areas may contain a mixture of fire severities occurring at multiple scales leading to heterogeneous landscapes (Heyerdahl et al. 2011). Nevertheless, we showed that variance in the mean number of fire occurrences per year changes with grain size, thereby rendering metrics such as MFRI incomplete, especially when heterogeneity is the management goal.

The median number of fire occurrences within our dataset was consistently low irrespective of spatial grain. The low number of fire occurrences is partially a function of the disconnected patterns of fire activity within the region, despite the maximum number of fire occurrences per spatial grain decreasing approximately 10-fold as grain increased (Table 1). Furthermore, the MFRI increased disproportionately as grain increased, exacerbating the bias caused by applying a mean fire treatment without consideration for variance at larger grain sizes. We recognized that the MFRI is constrained by the spatiotemporal extent and therefore will increase/decrease as spatiotemporal extent is defined. Applying a single MFRI to the entire Great Plains is ineffective and would misrepresent the regional fire diversity. Further disparate patterns were observed when reporting the % area that recorded a fire at each grain. Therefore, metrics such as % area burned and MFRI are only valid at a particular scale and generalizing these over a region should be avoided. The lack of consideration of scale and variance in fire regime classifications is likely to be precarious in other regions as well. Therefore, we propose that application of the MFRI is incomplete when variance is not considered. The importance of this finding is that we recommend caution when applying MFRI alone, so that it is not used to define a prescription, management target, fire regime, or policy.

Understanding how modern ecological systems have been simplified (e.g., application of mean fire treatments) requires a more complete understanding of the forces driving complexity at multiple spatiotemporal scales (Cumming and Collier 2005, Fuhlendorf et al. 2017). A fundamental premise in rangelands is that land management has simplified the heterogeneity inherent in these landscapes across multiple spatial scales (Fuhlendorf and Engle 2001, Limb et al. 2016), leading to major losses in the biological diversity and other ecosystem services endemic to the region. Although we do not have an independent dataset equal to the whole extent of our study area to test the relationship of MFRI and biodiversity, our results can be corroborated by several other studies showing clear differences in patterns of fire, such as between the northern (burns less frequently) and southern Great Plains (burns more frequently; Guyette et al. 2002) as well as localized exceptions (Mohler and Goodin 2012, Krueger et al. 2015) despite the high degree of landscape fragmentation in the region (Fuhlendorf et al. 2002, Hobbs et al. 2008).

Ecological data often include many sources of variability, while this study shows the importance of scale and variance when applying generalized mean fire metrics. Fire was a major driver of heterogeneity across scales (Guyette et al. 2002), and it is evident that understanding variance of fire patterns is scale-dependent. We therefore advocate for embracing variance in grassland fire activity, especially when reporting and applying fire return intervals to management or planning. Central tendency in fire return intervals need not be treated as a prescription, especially when rangelands are being managed for heterogeneity (Fuhlendorf et al. 2017). While fire occurrence has decreased across all scales from the pre-settlement era (Guyette et al. 2002), the Great Plains has experienced a marked increase in the variance in fire occurrence from grain size ranging from local sites to ecoregions (Level 3; Omernik 1995). This increase in variance contrasts with application of wildfire management, which operates under an objective of reducing variability and unpredictability in wildfire dynamics (Twidwell et al. 2016). Despite this information, researchers have not explored questions of grassland fire with respect to changes in the variance in fire occurrence (and other fire

regime characteristics) across scales. Our approach provides the foundation for further exploration of the role of fire regime variability across spatial scales in future studies.

In conclusion, the complex interactions between climate, social factors (e.g., policy and landowner decision-making), and land-use practices lead to varied timing (Roberts et al. 1999, Weir 2011) and fire patterns in the region. Our study shows that generalizing fire patterns to any particular scale is most effective when variance is considered. Failure to do so could lead to a misunderstanding of ecological effects or misplaced resources. These major discrepancies in fire activity are evident at all units within the Great Plains. Nevertheless, despite the low number of fire occurrences recorded in the region and the similarity in the mean number of fire occurrences between units, variance in fire numbers does decrease as grain size increases as predicted, while variance within units was more homogenous. Fire is one of a suite of ecological processes that affect systems and organisms in complex ways across scales as evidenced by grazing (Fuhlendorf and Engle 2001, Fuhlendorf et al. 2009) and vegetation dynamics (Fuhlendorf and Smeins 1999). This disconnect in fire activity between scales can result in a mismatch in policy and action (with complexities within each of these components) within the region. Our study, therefore, provides a deeper understanding into fire dynamics within the Great Plains region while emphasizing the importance of discussing variance in fire patterns within the appropriate context and scale.

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